

Spatial Analysis of Degradation and Deforestation: Land Use Conflict in the Peusangan Watershed

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ABSTRACT

This study aimed to analyze the spatial patterns of forest degradation and deforestation in the Peusangan Watershed, Aceh Province, Indonesia, from 2012 to 2024, and to evaluate their conformity with existing spatial planning regulations for sustainable land management. A descriptive quantitative study using multitemporal spatial analysis through Geographic Information System (GIS) and remote sensing approaches. The research was conducted in the Peusangan Watershed, which covers an area of approximately 255,543.99 hectares across several districts in Aceh Province, Indonesia. The analysis was carried out from March to August 2024 using land-cover data from 2012 to 2024. Land-cover maps were compiled from official sources and reclassified into 23 land-use categories. Multitemporal change detection and overlay analysis were performed using ArcGIS 10.8 to identify areas of degradation and deforestation. Degradation was defined as the transition from primary to secondary or shrub forest, while deforestation referred to the conversion of forest into non-forest uses such as agriculture or settlement. Spatial conformity with functional forest zones (Protection Forest, Production Forest, Limited Production Forest, Hunting Park, and Other Land Uses) was assessed. Field verification was conducted using GPS sampling points. The results showed that total forest degradation in the Peusangan Watershed from 2012 to 2024 reached 3,117.96 hectares, while total deforestation reached 17,223.35 hectares. The peak of both degradation and deforestation occurred during 2018–2019, with 1,689.16 hectares of degraded forest and 5,554.82 hectares of deforested land. The highest degradation occurred in the Permanent Production Forest (49.03%) and Protection Forest (46.49%), while deforestation was most dominant in Other Land Uses (44.59%) and Protection Forest (34.83%). Spatial overlay results revealed inconsistency between land-use implementation and existing spatial plans. The study concludes that the Peusangan Watershed has undergone significant forest degradation and deforestation, particularly between 2018 and 2019. Strengthening spatial planning enforcement, community-based monitoring, and rehabilitation programs supported by GIS and remote-sensing technologies are necessary to mitigate further forest loss and support sustainable watershed management.

Keywords: Deforestation; Forest Degradation; Peusangan Watershed; Remote Sensing; Geographic Information System (GIS); Protection Forest; Land Cover Change; Spatial Planning; Sustainable Management; Spatial Analysis.

1. Introduction

1.1. Background

The Peusangan Watershed in Aceh Province represents a critical landscape where these complex dynamics converge. Encompassing approximately 255,543.99 hectares across multiple districts, this watershed features a mosaic of forest designations including Protection Forests, Permanent Production Forests, and Limited Production Forests along with Areas for Other Land Uses (APL). As a primary water source for communities, agriculture, and the Peusangan hydropower system, the watershed's ecological integrity directly influences regional water security, energy production, and climate adaptation capacity.

Despite its ecological and socioeconomic significance, the Peusangan Watershed has experienced accelerating forest conversion and spatial planning inconsistencies in recent years. Existing research on land-cover change in Aceh has predominantly operated at provincial scales, lacking the granularity needed for effective watershed management. Furthermore, scholarly attention has disproportionately focused on deforestation (complete forest loss), while the more subtle yet equally detrimental process of forest degradation characterized by declining biomass and ecosystem function remains critically understudied. This gap is particularly problematic because degradation often precedes deforestation and can be equally damaging to ecosystem services.

The absence of comprehensive, watershed-specific analysis integrating both degradation and deforestation metrics, along with spatial planning compliance evaluation, has hampered effective policy intervention. Without spatially explicit and temporally dynamic evidence, conservation efforts and spatial planning enforcement remain inadequately targeted. This study addresses these research gaps by conducting a detailed multitemporal analysis (2012-2024) of forest degradation and deforestation patterns in the Peusangan Watershed. Through integrated remote sensing and GIS approaches, this research will delineate change trajectories, evaluate adherence to spatial planning protocols, and provide empirical foundations for targeted conservation strategies and sustainable watershed governance in Aceh.

1.2. Research Objectives

Based on the background described above, the study aims to achieve the following three objectives:

1. To analyze forest changes in the Peusangan Watershed (2012-2024) in order to identify the distribution and patterns of degradation and deforestation.
2. To evaluate the conformity of these changes with the regional spatial plan.
3. To provide a data-driven basis to support sustainable watershed management and forest rehabilitation policies in Aceh.

2. Materials and Methods

2.1. Study area

The study was conducted in the Peusangan Watershed (DAS Peusangan), Aceh Province, Indonesia. The watershed covers approximately 255,543.99 hectares and spans several administrative districts. Topography ranges from high-elevation headwaters (>1,000 m a.s.l.) to lowland plains near the outlet (<200 m a.s.l.), with varied slope classes and dominant soil types including Ultisols, Inceptisols and Entisols. The watershed contains multiple forest function zones (Protection Forest, Permanent Production Forest, Limited Production Forest, Hunting Park, and Areas for Other Land Uses / APL). Geographic coordinates, administrative boundaries, and sub-watershed delineations used in the analysis follow official spatial data from regional geospatial agencies.

2.2. Data sources and materials

The analysis used multi-source spatial data for the period 2012–2024, compiled from official and secondary sources as follows:

- a. Multitemporal land-cover/land-use maps for selected years (harmonized into a 23-class legend).
- b. Official functional forest zone maps and spatial planning (RTRW/forest area) from government agencies.
- c. Digital Elevation Model (DEM) for slope and elevation analysis.
- d. Ancillary data: administrative boundaries, river network, and sub-watershed polygons.
- e. Field validation data collected with handheld GPS during targeted ground-truth visits.

Software and hardware: ArcGIS 10.8 (ESRI) for spatial processing and overlay analysis; standard desktop GIS workstation; GPS handheld units for field validation.

2.3. Land-cover harmonization and classification

All land-cover datasets were reclassified and harmonized to a consistent 23-class scheme to ensure comparability across years. Harmonization steps included reprojection to a common coordinate system, resolution matching, and legend reconciliation to align class definitions (e.g., primary forest, secondary forest, shrub/scrub, mixed dryland agriculture, plantation, and settlement). Where source maps had differing thematic granularity, classes were aggregated or disaggregated according to a predefined crosswalk table to maintain semantic consistency.

2.4. Change detection and definition of change categories

Multitemporal change detection was conducted using map-to-map comparison and transition-matrix analysis in ArcGIS 10.8. For each pair of consecutive years (e.g., 2012→2014, ..., 2022→2024), a cross-tabulation (transition matrix) was produced to quantify class-to-class conversions and to calculate areal changes.

Change categories were defined as follows:

- a. Persistent forest (PF): areas classified as forest in both earlier and later dates.
- b. Persistent non-forest (PNF): areas non-forest in both dates.
- c. Deforestation (DEF): conversion from any forest class to any non-forest class (e.g., forest → agriculture/settlement/plantation).
- d. Reforestation (REF): conversion from non-forest to forest class.
- e. Degradation (DEG): transitions representing loss of forest structural/qualitative integrity without full conversion to non-forest (e.g., primary forest → secondary forest; secondary forest → shrub/scrub). Degradation was operationalized as a downshift in forest class quality according to the defined class hierarchy.

Areal change (hectare) for each category and each time interval was computed from the transition matrices. Annualized change rates were derived where appropriate.

2.5. Spatial conformity analysis with land-use planning

To assess alignment between observed land-cover change and designated functions, change maps were overlaid with official functional forest zone maps and regional spatial plans (RTRW). For each change polygon, the underlying land-use designation was recorded to identify instances of non-conforming land-use (e.g., conversion within Protection Forest). Summaries by functional zone (area and percent) were produced to highlight which zones experienced the greatest deforestation and degradation.

2.6. Accuracy assessment and field validation

An accuracy assessment protocol was applied to evaluate the reliability of change detection results. Where available, existing reference datasets and high-resolution imagery were used to validate classifications. In addition, targeted field validation was performed using GPS to collect ground-truth observations at representative sites

across sub-watersheds and across major land-cover classes. Confusion matrices were produced to compute overall accuracy, producer's and user's accuracies for major classes; the kappa statistic was calculated where appropriate. (Field validation details sampling strategy, number of reference points per class, and exact accuracy metrics follow the procedures described in the thesis documentation).

2.7. Data processing, analysis and outputs

All spatial analyses (reclassification, overlay, transition matrices, area calculations, zonal summaries) were performed in ArcGIS 10.8. Outputs included: multi-year land-cover maps, change maps for each interval, transition matrices, zonal statistics by functional forest zones, and cartographic products for visualization. Tabular results were exported to spreadsheet format for reporting and further statistical summaries. Key derived metrics include total area (hectare) of deforestation and degradation per period, period of peak change, and distribution of changes by spatial planning designation.

3. Results and Discussion

3.1. Dynamics of Land Cover Change in the Peusangan Watershed (2012-2024)

The results of the analysis of land cover changes in the Peusangan watershed between 2012 and 2024 show very significant land use dynamics. This data illustrates the shift in land use influenced by various socio-economic factors, land management policies, and pressures on natural resources (Lambin & Geist, 2006).

Although the data indicate an increase in primary dryland forest area from 8,606.65 hectares (2012) to 40,583.26 hectares (2024), this drastic expansion does not necessarily reflect successful restoration or natural ecosystem recovery. It is highly improbable that primary forests, which are old-growth, complex ecosystems, could regenerate naturally to such a significant extent over a mere 12-year period. Consequently, this apparent increase is far more likely attributable to reclassification or changes in mapping methodologies. As suggested in the literature (FAO, 2020), the increase most probably stems from data corrections, the use of higher-resolution satellite imagery, or revisions to operational definitions. These factors have led to areas previously classified as secondary forest or other well-vegetated land covers being re-categorized as primary forest. Therefore, this observed 'increase' represents an administrative and technical phenomenon in forest monitoring rather than a genuine indication of ecological improvement, and it indeed requires further ground-truthing for validation.

In contrast, Secondary Dryland Forests experienced a very drastic decrease in area of 43,192.99 hectares (16.90%), from 65,347.70 ha to 22,154.71 hectares. A similar decrease also occurred in the cover of Bushes which decreased by 59,432.05 hectares (23.26%). The large decline in these two categories indicates a shift in natural land and degraded land towards more intensive land use.

This land conversion is confirmed by a very significant increase in the area of plantations, namely from zero hectares in 2012 to 51,107.49 hectares (20.00%) in 2024. This growth signals a shift in land function towards an agribusiness-based economy, which has the potential to result in environmental degradation if not managed sustainably (Turner, Lambin, & Reenberg, 2007). In addition, there has been an increase in the area of settlements

from 1,927.81 hectares to 16,211.99 hectares, which indicates the existence of rapid urbanization processes that can negatively impact the fragmentation of habitats and water resources (Seto et al., 2012).

3.2. Spatial Analysis of Forest Degradation

Analysis of land cover changes from 2012 to 2024 shows the occurrence of forest degradation, which in this study is defined as the change in land cover from Primary Dryland Forests to Secondary Dryland Forests. The total area of forest degradation in the Peusangan watershed during the period reached 3,117.96 hectares. The rate of degradation fluctuates, where there was no recorded degradation in the 2012-2015 period, but began to be identified in 2015-2016 (453.58 hectares) and reached its peak in the 2018-2019 period with an area of 1,689.16 hectares. After the peak period, the rate of degradation decreased significantly. The area of forest degradation per year period can be seen in Figure 1.

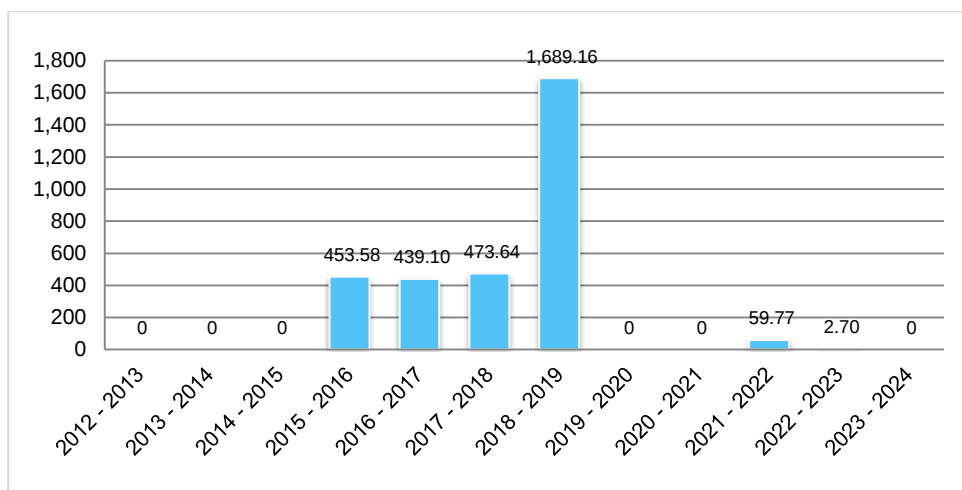


Figure 1. Extent of forest degradation in the Peusangan watershed

The increase in forest degradation, especially during peak periods, is caused by various interacting factors. Land conversion for agriculture and plantations is one of the main causes (Arfan, 2021). The development of road infrastructure also provides easier access to forests and triggers ecosystem destruction (Gaveau, 2021). Other factors include forest fires (Handayani, 2021), illegal logging activities (Adriani et al., 2022), community dependence due to poverty (Dekiwati, 2020), and ineffective management policies (Prasetyo, 2021).

3.3. Distribution of Degradation in Regional Functions

To analyze more deeply, the area of forest degradation was *overlaid* with spatial data on the function of forest areas (SK 580/Menlhk/Setjen/Set.1/12/2018). The results showed that degradation occurred in 4 out of 5 existing regional functions. The distribution of forest degradation by period by area function is presented in Figure 2.

The data shows that the total degradation (3,117.96 hectares) is distributed almost evenly in two main areas: Permanent Production Forest (HP) of 1,528.59 hectares (49.03%) and Protected Forest (HL) of 1,449.65 hectares (46.49%). The temporal pattern shows that the peak of degradation in 2018-2019 occurred predominantly in Permanent Production Forests (1,234.03 hectares), which is in line with the findings of Margono et al. (2014) that conversion pressure on HP often increases for large-scale plantation land clearing.

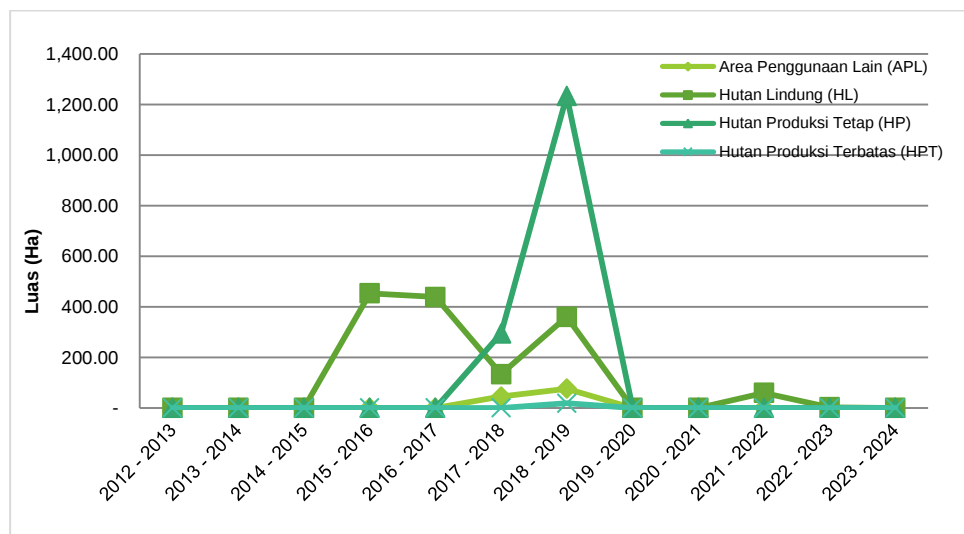


Figure 2. Forest Degradation Area in the Peusangan Watershed based on the Forest Area Function

The most worrying finding is the high level of degradation in Protected Forests, which has consistently occurred since 2015-2016. This phenomenon is consistent with the report of Gaveau et al. (2021) which highlights that encroachment occurs not only in production forests but also in protected areas, often related to illegal activities. Overall, this distribution indicates that production forest areas are the most vulnerable areas, and the 2018–2019 period is a critical point that requires attention in conservation strategies.

3.4. Spatial Analysis of Deforestation

Deforestation, defined as the change in land cover from forested (H) to non-forested (NH) group, occurs on a much larger scale. The total area of forest deforestation in the Peusangan watershed during the period 2012 – 2024 reached 17,223.35 hectares. The temporal pattern of deforestation (Figure 3) shows sharp fluctuations.

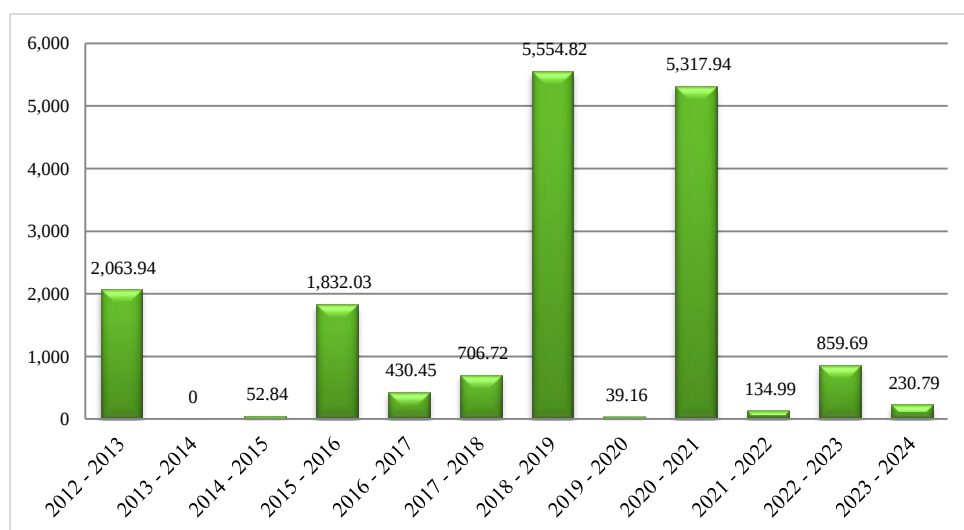


Figure 3. Forest deforestation in the Peusangan watershed

Significant deforestation occurred in 2012–2013 (2,063.94 hectares), likely related to plantation expansion. This rate slowed down drastically in 2014-2015 (52.84 hectares), allegedly due to the decline in CPO prices (Gaveau et al., 2014). The largest spike in deforestation during the observation period occurred in 2018–2019, which was

5,554.82 hectares. The driving factors are suspected to include the increase in CPO prices, spatial planning policies, and forest fires (Tacconi, 2016). Interestingly, after dropping drastically in 2019-2020 (39.16 hectares), deforestation soared again in 2020-2021 covering an area of 5,317.94 hectares. Gaveau et al. (2021) explained that mobility restrictions during the COVID-19 pandemic are likely to reduce the intensity of field patrols, resulting in an increase in illegal land clearing activities.

3.5. Distribution of Deforestation in Regional Functions

Overlay analysis with regional function maps (Figure 4) shows that deforestation occurs in 4 regional functions. Based on regional function, the largest deforestation occurred in Other Use Areas (APL) with a total loss of 7,679.77 hectares (44.59%). This is in line with the findings of Margono et al. (2014) that APL has a high vulnerability to conversion to agriculture and plantations due to its legal status.

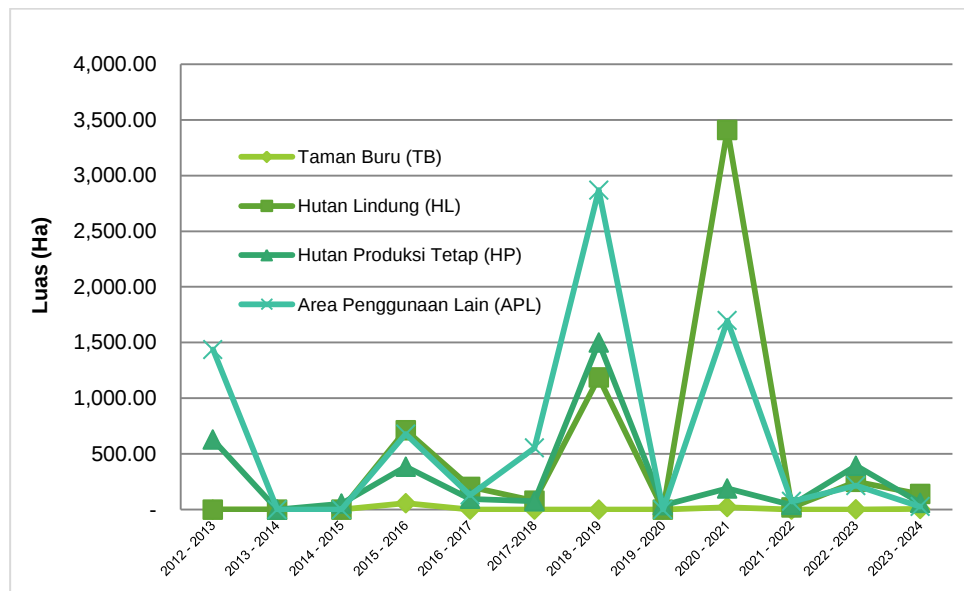


Figure 4. Forest deforestation area in the Peusangan watershed based on the function of the forest area

However, the most critical finding is that Protected Forests (HL) experienced massive deforestation of 5,998.25 hectares (34.83%), with the peak loss occurring in 2020–2021 (3,410.11 hectares). This is generally triggered by the opening of road access and illegal land conversion (Kusmana, 2017). Meanwhile, Permanent Production Forests (HP) lost 3,460.55 hectares (20.09%), which according to Maryudi and Myers (2018) usually comes from commercial logging and encroachment.

3.6. Analysis of Conformity with the Spatial Pattern Plan

The core findings of this study are the analysis of the compatibility between the facts of degradation and deforestation with the Aceh Province Spatial Pattern Plan (RTRW). The spatial pattern plan is used as the basis for controlling the use of space to match ecological capacity (Fitriani & Hidayat, 2019). In the Peusangan watershed, the spatial pattern plan is divided into Protected Areas (23.20%) and Cultivation Areas (76.80%). Cultivation areas are dominated by the allocation of People's Plantations (34.44%).

3.6.1. Inconsistencies in the Shelter Pattern

Overlay analysis shows that there is a serious conflict of space utilization. Areas that legally have a protection function actually experience high conversion pressure (Narendra et al., 2021).

In the case of degradation, the Protected Forest Spatial Pattern Plan experienced degradation of 1,449.16 hectares (48.2%) of the total degradation, almost equivalent to the degradation in Production Forests (1,528.59 hectares). This shows that the Protected Forest area is experiencing enormous human activity pressure, indicating encroachment, illegal logging, and shifting farming activities (Purnomo et al., 2020).

In the case of deforestation (Table 1), the non-conformity is more fatal. The Protected Forest Spatial Pattern Plan is the second most affected area, with a total loss of forest cover reaching 6,021.43 hectares. Deforestation was also recorded significantly in the River Border Protection Area (336.15 hectares), the Water Infiltration Protected Area (85.28 hectares), and the Buru Park (84.41 hectares).

This phenomenon shows a real incompatibility between the actual use of space and the allocation of space in the RTRW. Weak control of space use (Dewi et al., 2020) and law enforcement cause protected areas that should be preserved (Margono et al., 2014) to be used for cultivation activities.

3.6.2. Conversion Drivers in Cultivation Space Patterns

On the Cultivation Zone side, deforestation data (Table 1) confirms that the main driver of forest loss is the expansion of People's Plantations, which recorded the highest deforestation rate at 7,073.45 hectares.

Table 1. Area of Forest Degradation based on the Spatial Pattern of the Peusangan Watershed

Rencana Pola Ruang	Luas Degradasi Hutan (Ha)/ Tahun													Total
	2012 - 2013	2013 - 2014	2014 - 2015	2015 - 2016	2016 - 2017	2017 - 2018	2018 - 2019	2019 - 2020	2020 - 2021	2021 - 2022	2022 - 2023	2023 - 2024		
Hutan Lindung	0	0	0	453,58	439,10	133,87	360,14	0	0	59,77	2,70	0	1.449,16	
Kawasan Lindung Sempadan Sungai	0	0	0	0	0	0	45,55	0	0	0	0	0	45,55	
Hutan Produksi	0	0	0	0	0	294,57	1.234,03	0	0	0	0	0	1.528,59	
Hutan Produksi Terbatas	0	0	0	0	0	0	18,27	0	0	0	0	0	18,27	
Perkebunan Rakyat	0	0	0	0	0	45,21	29,69	0	0	0	0	0	74,90	
Pemukiman Perdesaan	0	0	0	0	0	0	1,49	0	0	0	0	0	1,49	
Total	0	0	0	453,58	439,10	473,64	1.689,16	0	0	59,77	2,70	0	3.117,96	

Table 2. Deforestation Area based on the Spatial Pattern of the Peusangan Watershed

Rencana Pola Ruang	Luas Deforestasi (Ha)/ Tahun													Total
	2012 - 2013	2013 - 2014	2014 - 2015	2015 - 2016	2016 - 2017	2017 - 2018	2018 - 2019	2019 - 2020	2020 - 2021	2021 - 2022	2022 - 2023	2023 - 2024		
Hutan Lindung	0	0	0	712,38	203,45	78,48	1.185,59	0	3.413,06	20,35	249,07	139,12	6.001,50	
Kawasan Lindung Resapan Air	14,90	0	0	0	0	70,38	0	0	0	0	0	0	85,28	
Kawasan Lindung Sempadan Danau	0	0	0	0	0	0	0	0	12,92	0	0	0	12,92	
Kawasan Lindung Sempadan Sungai	21,68	0	0	18,95	5,67	21,09	205,99	0	23,61	0	13,54	6,11	316,64	
Taman Buru Lingga Isaq	0	0	0	56,47	0	0	0,07	0	21,57	0	1,30	5,07	84,48	
Hutan Produksi	633,25	0	0,17	386,27	96,27	75,20	1.499,55	39,16	189,91	41,90	393,60	59,66	3.414,95	
Kawasan Pariwisata	0	0	0	0	0	0	0	0	0,09	0	0	0	0,09	
Kawasan Peternakan	0	0	0	0	0	0	0	0	0,07	0	0	0	0,07	
Perkebunan Besar	63,25	0	0	53,58	0,01	12,22	108,53	0	0	0	0	0	237,59	
Perkebunan Rakyat	1.110,41	0	0	533,67	111,17	205,00	2.396,23	0	980,61	72,74	151,02	13,59	5.574,45	
Pemukiman Perdesaan	0	0	0	0	0	0	0	0	17,48	0	0,24	0	17,73	
Pemukiman Perkotaan	0	0	0	0	0	0	0	0	32,14	0	0	0	32,14	
Pertanian Lahan Basah	0	0	0	0	0	0	0	0	230,10	0	0	0	230,10	
Pertanian Lahan Kering	216,68	0	52,66	69,86	13,87	244,35	155,28	0	390,83	0	50,84	7,24	1.201,60	
Tubuh Air	3,77	0	0	0,84	0	0	3,58	0	5,55	0	0,07	0	13,80	
Total	2.063,94	0	52,84	1.832,03	430,45	706,72	5.554,82	39,16	5.317,94	134,99	859,69	230,79	17.223,35	

In addition, the designation of Production Forests has been deforested covering an area of 3,784.54 hectares, and Dryland Agriculture covering an area of 1,201.75 hectares. Conversion of forest functions for production purposes

without paying attention to the carrying capacity of the environment can lead to a decrease in land quality and the risk of long-term degradation (Widiatmaka et al., 2016). Overall, deforestation data in the Peusangan watershed illustrates the massive pressure on forest cover derived from community activities (plantation expansion) and is exacerbated by weak spatial control and limited implementation of RTRW in protected areas.

4. Conclusion

Multitemporal spatial analysis of the Peusangan Watershed from 2012 to 2024 confirms that significant land cover changes have occurred. These dynamics were primarily driven by the large-scale conversion of Secondary Dryland Forest (a decrease of 43,192.99 hectares) and Shrublands (a decrease of 59,432.05 hectares) into cultivated areas, notably Plantations (which expanded to 51,107.49 hectares) and Settlements (which grew by 14,284.18 hectares).

The study's findings reveal that total forest degradation (defined as Primary Forest converting to Secondary Forest) reached 3,117.96 hectares, with the highest rate recorded during the 2018–2019 period. Deforestation (the conversion of Forest to Non-Forest areas) occurred on a far more massive scale, totaling 17,223.35 hectares, with two distinct peak periods observed in 2018–2019 and 2020–2021.

The most critical finding of this research is the significant discrepancy between actual land change realities and the designated Spatial Plan (RTRW). Overlay analysis indicated that degradation was not only concentrated in Permanent Production Forests (49.03%) but also occurred extensively within Protection Forest areas (46.49%). A similar pattern emerged for deforestation, where Protection Forests accounted for 34.83% (5,998.25 hectares) of the total forest loss. This demonstrates a failure of protective functions in a zone legally designated for conservation. Meanwhile, within designated cultivation zones, the primary driver of deforestation was the expansion of Smallholder Plantations (7,073.45 hectares). These findings indicate that the land conversion rate in the Peusangan Watershed has surpassed its carrying capacity and disregarded spatial planning directives. This necessitates an urgent evaluation of the RTRW's implementation and the reinforcement of conservation strategies.

Declarations

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Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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